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IMPACT IONIZATION STUDY

FINAL REPORT

Grant NASA NAGW-225

by



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OUTLINE

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1. Introduction

The purpose of this work was to carry out a preliminary study of the impact ionization phenomenon which has been recently observed on certain spacecraft. The phenomenon occurs when a neutral atom, molecule, or ion strikes a surface with sufficient kinetic energy that either the incident neutral or atoms on the surface are ionized, with subsequent escape of ions and/or electrons. The released ions and electrons can interfere with measurements on the spacecraft by confusing interpretation of the data. On the other hand, there is the possibility that the effect could be developed into a diagnostic tool for investigating neutral atmospheric species or for studying physical processes on spacecraft surfaces.

The impact ionization phenomenon has been observed on the Pioneer Orbiter at Venus and on the Atmospheric Explorer C satellite in earth orbit. On the Atmospheric Explorer C satellite in earth orbit, the effect was observed by ion measurements with an ion mass spectrometer and with a retarding potential analyzer (Hanson et al, 1981). The ions were identified as coming from the spacecraft because of their low energy (about 1 eV in the spacecraft reference frame) in contrast with the normal ram energy of atmospheric ions due to the spacecraft motion. Alkali ions, Na^+ , and K^+ , were observed as well as non-ionospheric NO^+ and O_2^+ . All these except NO^+ were apparently released by impacts of neutral N_2 with the surface. Their production was probably related to surface contamination since the effect decreased with a time constant of about six weeks. Hanson et al (1981) were able to estimate the efficiency of the impact process in releasing ions to be on the order of 10^{-6} for N_2 impact and on the order of 10^{-4} for the release of alkali atoms produced by impact of O^+ at higher altitudes. Again, the variation of the effect with altitude seemed to follow the scale height for the impacting atmospheric ion or neutral.

The effort under the present grant was primarily concerned with the observations of the impact ionization effect on the Langmuir probe experiment on the Pioneer Venus Orbiter spacecraft. In the following sections we first describe the spacecraft and the experiment. We then describe the observations of the impact phenomenon and the analysis of this effect that we have carried out. Finally, we give some recommendations as to what would be needed for a more complete investigative program.

2. The Pioneer Venus Spacecraft and the Langmuir Probe Experiment.

The Pioneer Venus Orbiter was launched on May 20, 1978 and reached Venus on December 4, 1978, when it was inserted into orbit about Venus. The spacecraft is cylindrical in shape, about 8 feet in diameter and 4 feet in height. Figure 1 shows a crude sketch of the spacecraft with the location of the two Langmuir probes. The Pioneer Venus program is described by Collin (1980) in a special issue of the Journal of Geophysical Research which contains also many of the early scientific results. The Langmuir probe experiment has been described by Krehbiel et al (1980) in a special issue of the IEEE Transactions on Geoscience and Remote Sensing.

Orbit periapsis was between 150 and 200 km in the Venus ionosphere, and apoapsis was at an altitude of about 67000 km.

The Langmuir probe instrumentation system consisted of two cylindrical sensors and a central electronics unit. The radial sensor was mounted at the end of a 1 m boom so that after deployment the sensor was perpendicular to the spacecraft spin axis. The axial probe was mounted on a fixed boom placing it 0.4 m above the spacecraft forward surface

and parallel to the spin axis. Each sensor had an applied voltage sweep every half second during which time the current was measured. The range of sweep voltage was adapted from previous sweeps so that good resolution would be obtained in that part of the current/voltage curve which gives information on the plasma: the local electron and ion densities and temperatures and also the spacecraft potential. The default voltage sweep was from about -10 volts to +3 volts.

The instrument obtained the ion and electron densities and temperatures and spacecraft potential by means of on-board data processing. Thus the current/voltage curves were not in general telemetered back to earth. However, every 8 sec one of the current/voltage curves from one sensor was sent back, alternating every 8 sec between the two sensors. Thus each sensor sends back a current/voltage curve every 16 sec. The spin period of the spacecraft was 12 sec. Consequently, the responses of the two sensors could not be compared in detail at the same phase of the spacecraft spin, except by waiting for two spin periods.

3. Description of the Impact Ionization Effect

Figure 2 shows two sets of current/voltage curves obtained from the radial and axial probes during a periapsis pass. This data was obtained during orbit #421 on January 30, 1980. The data was displayed on the UCSD computer picture system in a three-dimensional format where the current is plotted on a logarithmic scale on the vertical axis, the voltage is plotted horizontally, and the successive curves as a function of time are displayed as a function of depth away from the viewer. There is a discontinuity on the vertical scale where the current changes sign. (The origin of the current/voltage axes is shown as a line along the time axis.) The left-hand set of curves are from the radial

probe, and the right-hand set from the axial probe. The data were taken during a five minute period centered approximately at the time of periapsis.

The data from the axial probe (on the right) show a distinct change in character as the spacecraft goes through periapsis, whereas the data from the radial probe shows no such change. In these curves electron current to the probe is upwards and ion current is downwards. The data from the axial probe show that the electron current begins to increase at a much smaller (less positive) value of the voltage. This effect shows as a bulge in the profiles. In addition, the curves show a secondary bump in the electron current at high positive voltages.

The unusual character of the current/voltage curves seen by the axial probe made it difficult for the on-board data processing program to interpret the data in terms of the plasma properties. Consequently, the voltage sweep range went to the default value in which the voltage was swept from -10 volts to +3 volts. This is the reason for the greater horizontal extent of the curves for the axial probe when compared to the curves for the radial probe.

The electron current measured by the axial probe as the probe voltage goes through zero volts can be interpreted as an electron density. This "impact generated" electron density is shown in Figure 3 as a function of altitude, along with the neutral CO_2 gas density. It is apparent that there is a very strong correlation between the neutral CO_2 density and this electron density. It is this correlation that led the experimenters to believe that this effect must be produced by the impact of the neutral gas.

4. Analysis of Data

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UCSD has received through Larry Brace at Goddard Space Flight Center five sets of data from the Langmuir probe experiment on the Pioneer Venus Orbiter. The sets consist of five passes through periaapsis, with each pass containing about 15 min of current/voltage curves. Each of the data sets exhibits the impact ionization effect. UCSD has prepared computer programs that read this data into the UCSD computer and display it in various formats. Interactive computer programs have been written for analysis of the data.

The usual equations for the collection of ionospheric ions and electrons by the cylindrical Langmuir probe in the absence of ionization impact effects are given below in equations (1) through (4):

$$I_i = \frac{N_i A e W}{\pi} \left[1 + \frac{k T_i}{m_i W^2} - \frac{2eV}{m_i W^2} \right]^{1/2} \quad (1)$$

$$\text{for } V \leq \frac{m_i W^2}{2e} + \frac{k T_i}{2e}$$

$$I_i = 0 \quad (2)$$

$$\text{for } V > \frac{m_i W^2}{2e} + \frac{k T_i}{2e}$$

Here, N_i is the ion density, A the area of the probe, e the magnitude of the ion or electron charge. W is the product of the spacecraft velocity and the cosine of the angle γ between the probe normal and the direction of motion. T_i is the ion temperature, m_i the ion mass, and V the voltage of the probe with respect to the plasma. Thus $V = V_p + V_{sc}$, where V_p is the voltage of the probe with respect to the spacecraft, and V_{sc} is the spacecraft potential.

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The equations for electron collection are:

$$I_e = - AN_e e \left(\frac{kT}{2\pi m_e} \right)^{1/2} \exp \left(\frac{eV}{kT_e} \right) \quad (3)$$

for $V \leq 0$

$$I_e = - AN_e e \left(\frac{kT}{2\pi m_e} \right)^{1/2} \left(1 + \frac{4eV}{\pi kT_e} \right)^{1/2} \quad (4)$$

for $V \geq 0$

where N_e is the electron density, assumed to be the same as the ion density, T_e is the electron temperature, and m_e the electron mass.

Figures 4 and 5 show current/voltage curves taken on orbit 421 (January 30, 1980) when the spacecraft was at an altitude of about 152 km. In these figures, electron current is upwards and ion current is shown as downwards, or negative. Note the different scales for the negative and positive currents in Figure 4. The solid curves refer to data points taken by the axial and radial probes. The letters "A" and "R" are theoretical points for the axial and radial probes respectively from the above equations, using values for the ionospheric densities and temperatures that provide a good fit to the data from the radial probe. The density of $4.5 \times 10^5 \text{ cm}^{-3}$ and temperature of 1500 degrees are quite close to what the on-board data processing procedure obtained. The spacecraft potential is about -1 volt. In Figure 5 where the data from the radial probe has been plotted with higher resolution, the values for the temperature and density have been adjusted slightly, and it

can be seen that the theoretical curves are an excellent fit to the data from the radial probe.

When the spacecraft is not close to periapsis, the theoretical points as a rule fit the data from both probes quite well, when the different angles of attack of the two probes are taken into account. Here, it is obvious that the usual theory does not describe well the data from the axial probe. The on-board processor has responded to the unusual data by increasing the range of the sweep voltage to the default range. One of the usual characteristics of the current/voltage curve is the steep rise of the electron current as the probe goes positive with respect to the plasma, i.e. when V_p exceeds V_{sc} . Here, the rise in the electron current to the axial probe occurs when the probe voltage is much less positive than the value for which the rise occurs for the radial probe. This rise in electron current is what is responsible for the distinctive bulge in the curve profiles shown in Figure 2.

The rise in electron current as the axial probe approaches zero volts with respect to the spacecraft can be explained by postulating that the spacecraft itself is a source of electrons. The correlation of the extra electrons with the neutral CO^2 gas density shown in Figure 3 suggests that the impact of the CO^2 molecules is knocking out secondary electrons from the spacecraft surface, and that these electrons are then being collected by the axial probe. However, this cannot be the whole story, since the current to the axial probe is more positive than the usual theory predicts for voltages more negative than about -2 volts. This can be explained if secondary electrons from the probe itself are taken into account. At negative voltages, all secondary electrons from the probe itself escape, and a positive current (negative current in the figure) is registered. However, as the probe voltage approaches zero with respect to the spacecraft, secondary electrons from the

spacecraft surface can be collected and diminish this current. This leads to the rise in electron current as the probe voltage approaches zero.

Thus we are led to the model for the impact ionization effect that is shown in Figure 6. Incoming CO_2 molecules impact primarily the top of the spacecraft where they knock out secondary electrons. Some of these electrons escape to the vicinity of the axial probe where they can be collected. In addition, CO_2 molecules can impact the axial probe itself and cause secondary emission of electrons. As long as the probe is negative these electrons will escape. When the probe goes positive, some of the secondary electrons will return to the probe.

We have modelled these secondary electron currents by applying the usual orbit-limited cylindrical Langmuir probe theory to this situation where the probe itself is the source of the electrons. Equations (5) through (7) give these secondary electron currents:

$$I = I_0 \left[-1 + \left(\frac{\cos \alpha_T}{\cos \alpha_A} \right) \frac{\pi}{4} \exp \left(\frac{eV_p}{kT_s} \right) \right] \quad (5)$$

for $V_p \leq 0$

$$I = I_0 \left[-\exp \left(\frac{-eV_p}{kT_s} \right) + \left(\frac{\cos \alpha_T}{\cos \alpha_A} \right) \frac{\pi}{4} \left(1 + \frac{4eV_p}{\pi kT_s} \right) \right] \quad (6)$$

for $V_p \geq 0$

where

$$I_0 = 2rL e Y N_c W \quad (7)$$

These equations use the same symbols as in the previous equations, with the addition of the angle α_T between the ram direction and the normal to the top of the spacecraft. The CO_2 molecular density is N_0 ; r and L are the radius and length of the axial probe; Y is the secondary electron yield for a CO_2 molecular impact; and T_s is the temperature of the secondary electrons. It has been assumed that the secondary electrons are emitted isotropically with a Maxwellian velocity distribution. The theory requires a solid angle factor for the emitting spacecraft surface as seen by the probe. A factor π (one fourth of the unit sphere) was assumed.

Figure 7 exhibits the same data as Figure 4, but the theoretical points for the axial data include the effects of impact-produced secondary electrons as given by equations (5) through (7). A secondary yield of 10^{-3} and a secondary electron temperature of 2.5 eV were used. These were the only free parameters, since the neutral CO_2 density was known to be close to 10^9 cm^{-3} at this altitude. Secondary electron temperatures from photoemission and from incident electron and ion impact are known to be on the order of 2 to 3 eV, so that 2.5 eV appears to be a very reasonable choice for T_s .

There is very little data on the yields for secondary electron emission upon neutral atom or molecule impact. However, yields for electron emission on neutral particle impact should be similar to those for ion impact. The reason for this is that low energy ions (below a few hundred eV) are neutralized just before impact by attachment of an electron produced by field-emission, and actually hit the surface as a neutral. Knudsen and Harris (1973) have obtained secondary electron yields for CO_2 ion impact in the laboratory and for other ions in both laboratory and space experiments. Some of their data is shown in Figure 8. At 22 eV for CO_2 impact, which is the energy at which the CO_2 molecules in the Venus atmosphere are striking the

spacecraft, Figure 8 shows yields between 10^{-4} and 10^{-3} . This is in reasonable agreement with the value of 10^{-5} used to fit the data in Figure 7. The actual yield should probably be somewhat lower than this since the value of 10^9 cm^{-3} for the neutral CO_2 concentration is probably somewhat low. A value of 2 or 3×10^9 is probably better for an altitude of 153 km, according to some of the neutral atmosphere models for Venus.

It is apparent that the theoretical points fit the axial data well for negative probe voltages. However, when the probe is positive, the theoretical points deviate markedly from the data. This is seen even more clearly in Figure 9, where the same data is plotted on an expanded scale (note again the different scales for negative and positive currents). The data (solid curve) for the axial probe do not show the steep rise in the electron current until the probe voltage is about +2 volts, whereas the theoretical points (marked "A") begin to rise at about +1 volt. A probe voltage of +1 volt (with respect to the spacecraft) is the voltage at which the probe would be positive with respect to the plasma and thus should begin to collect the ionospheric electrons at a rapid rate.

The most likely explanation for the differences between the data and the theory for positive probe voltages involves two effects. First, the secondary electrons provide space charge which can create a negative potential barrier in the vicinity of the probe. This will make it more difficult for the plasma electrons to be collected by the probe, until the probe has gone sufficiently positive that the barrier potential is reduced. Second, at larger positive probe potentials, the probe begins to behave as a sphere rather than as a cylinder. This will have the effect of increasing the slope of the current/voltage curve at large positive potentials, as the data (solid curve in Figure 9) indicates.

A quantitative verification of these effects as the explanation for the discrepancy between the theory and the data at positive probe potentials must await detailed numerical modelling. Dr. Lee Parker has begun to study this problem and has developed a preliminary model which shows how a potential barrier could occur in the vicinity of the probe. Figure 10, taken from his report (Parker, 1982), shows how potential profiles near the probe when the probe is immersed in the spacecraft sheath can develop a barrier. This particular calculation required a large negative excursion in potential near the spacecraft, assumed to be caused by the negative secondary electron cloud. As the probe voltage approaches zero (with respect to space), a barrier occurs outside the probe position (denoted by V_b) which would act to prevent the collection of ionospheric electrons. The barrier does not disappear until the probe has gone to about +1 volt with respect to space (+2 volts with respect to the spacecraft). In Figure 10, the voltage V_c is the critical voltage at which the barrier disappears.

5. Conclusions

We believe that we have identified the emission of secondary electrons caused by impact of neutral CO_2 molecules as the mechanism for the anomalous effects observed during the periapsis passages of the Pioneer Venus Orbiter. We have been able to model the current/voltage curves for the axial Langmuir probe and have found quantitative agreement with the model for negative probe voltages, using reasonable values for the secondary electron yields and temperatures. We have found that it was necessary to take into account both emission from the spacecraft surface and also from the probe itself to obtain agreement between the observed current/voltage curves and the model.

We make the following recommendations for future work:

(1) The numerical modelling should be extended.

First, the transition from cylindrical behavior to spherical behavior of the probe should be modelled. This transition probably occurs when the radius of the sheath about the probe becomes comparable to the length of the probe. Second, the negative space charge sheath caused by the secondary electron cloud should be investigated further. The model of Lee Parker assumed that the undisturbed sheath in the vicinity of the probe (undisturbed by the presence of the probe) should be at a potential of about -1 volt. This assumption was suggested by the experimenters, and was based on the behavior of the axial current/voltage curve which did not see the increasing plasma electron current until the probe was a volt more positive than space potential. However, in our interpretation, this effect is due to the barrier, and it is unnecessary to postulate that the undisturbed sheath in the vicinity of the probe be at a potential of -1 volt. This assumption should be relaxed to see if a barrier could be obtained without as large a negative excursion in the spacecraft sheath potential that is shown in Fig. 10. One problem with this large excursion in potential is that it requires a very large secondary electron density and therefore yield.

(2) It is not clear why the radial probe seems to be relatively immune to the impact effect. Part of the reason must be the shielding of the radial probe from the inflowing neutral gas during the portion of the spin cycle when the probe is behind the spacecraft. In addition, it may be that there are much fewer secondary electrons around the sides of the spacecraft as opposed to above the top surface, so that a negative sheath is not formed in the vicinity of the probe. However, this aspect of the data needs further study. A comparison of the two probes should be made for as many angular positions as possible during the spacecraft spin, and the behavior of the radial probe should be modelled

numeric lly also.

(3) A literature search should be carried out to ascertain what information is available on secondary electron yields for neutral atom and molecule impact. This effect occurs in laboratory plasma devices such as the fusion machines, and it may be that some of the national laboratories have accumulated data in unpublished in-house reports.

In addition to this report, some preliminary results from this work were described at a special working group meeting sponsored by ESTEC concerning the GIOTTO Plasma Environment. The GIOTTO mission is planning on sending a spacecraft to Halley's comet, and any impact ionization effects could be especially important on this mission because of the high relative velocity between the spacecraft and the cometary atmosphere. At Halley's comet the relative velocity is about 70 km/sec, which would result in an impact energy approaching 1 keV for CO_2 molecules, which are an important constituent of the atmosphere. At this impact energy, the secondary electron yield for ion impact is near unity, and the secondary electrons could dominate the local plasma electron density.

A paper describing this work will eventually be prepared after further modelling work has been carried out. Meanwhile, a talk describing the results up to this point will be presented at the December, 1982, meeting of the AGU (Whipple, Brace and Parker, 1982).

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- Whipple, E. C., L. H. Brace, and L. W. Parker, "Impact Ionization Effects on Pioneer Venus Oribiter," EOS, 45, 1074, 1982.

FIGURE CAPTIONS

1. Sketch of the Pioneer/Venus Orbiter showing locations of the Langmuir probe experiments.
2. A three-dimensional display on the UCSD computer picture system showing Langmuir probe data during periapsis from orbit #421, on January 30, 1980. The current axis is vertical on a logarithmic scale, with electron current upwards; the voltage axis is horizontal, and time increases with depth into the picture. The data from the radial probe is on the left, and from the axial probe on the right. The impact ionization effect can be seen in the "bulge" in the current/voltage curves for the axial probe.
3. A plot of the impact-produced secondary electron density along with the neutral CO_2 gas density versus altitude above Venus.
4. Current/voltage curves from the axial and radial probes from orbit #421 at about 152 km altitude. The solid curves are data, and the letters "A" and "R" refer to theoretical points for the axial and radial probes respectively. Note the difference in the current scale for positive and negative currents. The voltage here is with respect to the spacecraft. The theoretical points here include only effects from ion and electron collection from the ionospheric plasma.
5. The radial current/voltage curve of Figure 4 plotted with greater resolution. The line is data and the letters labelled "R" are theoretical points.
6. A model for the impact ionization effect and the secondary electron emission calculation.

7. The same current/voltage curves as in Figure 4, but now the theoretical points include the effects from impact of the neutral CO_2 molecules.

8. Data on secondary electron yields from ion impact, from laboratory and space experiments of Knudsen and Harris (1973).

9. The same current/voltage curves as in Figures 4 and 7, but plotted on an expanded scale to show the data and theoretical points at positive probe voltages.

10. Schematic potential profiles for the axial probe in the impact-generated space charge sheath of the spacecraft, showing how a potential barrier could be produced near the probe (from Parker, 1982).

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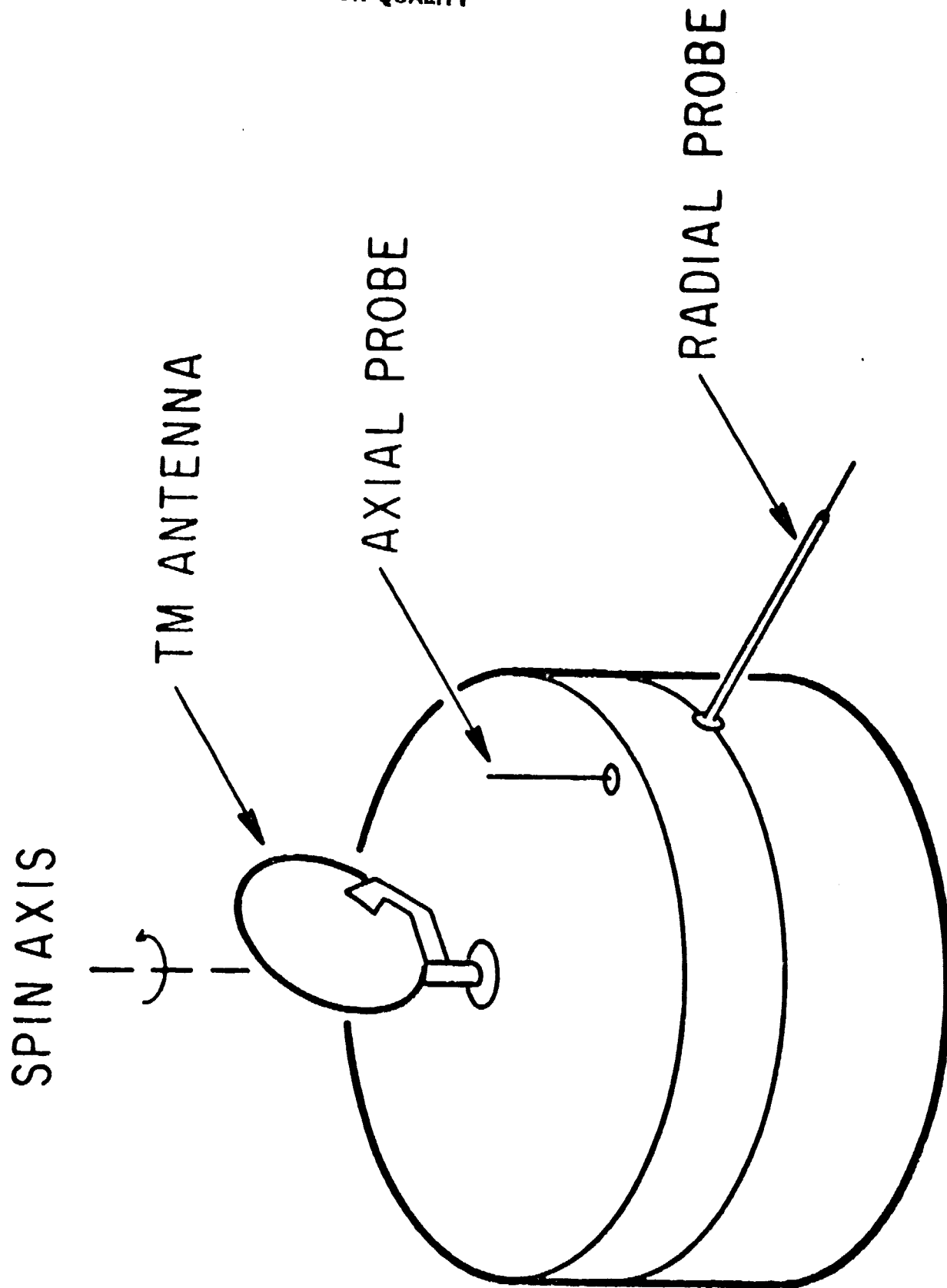


Figure 1

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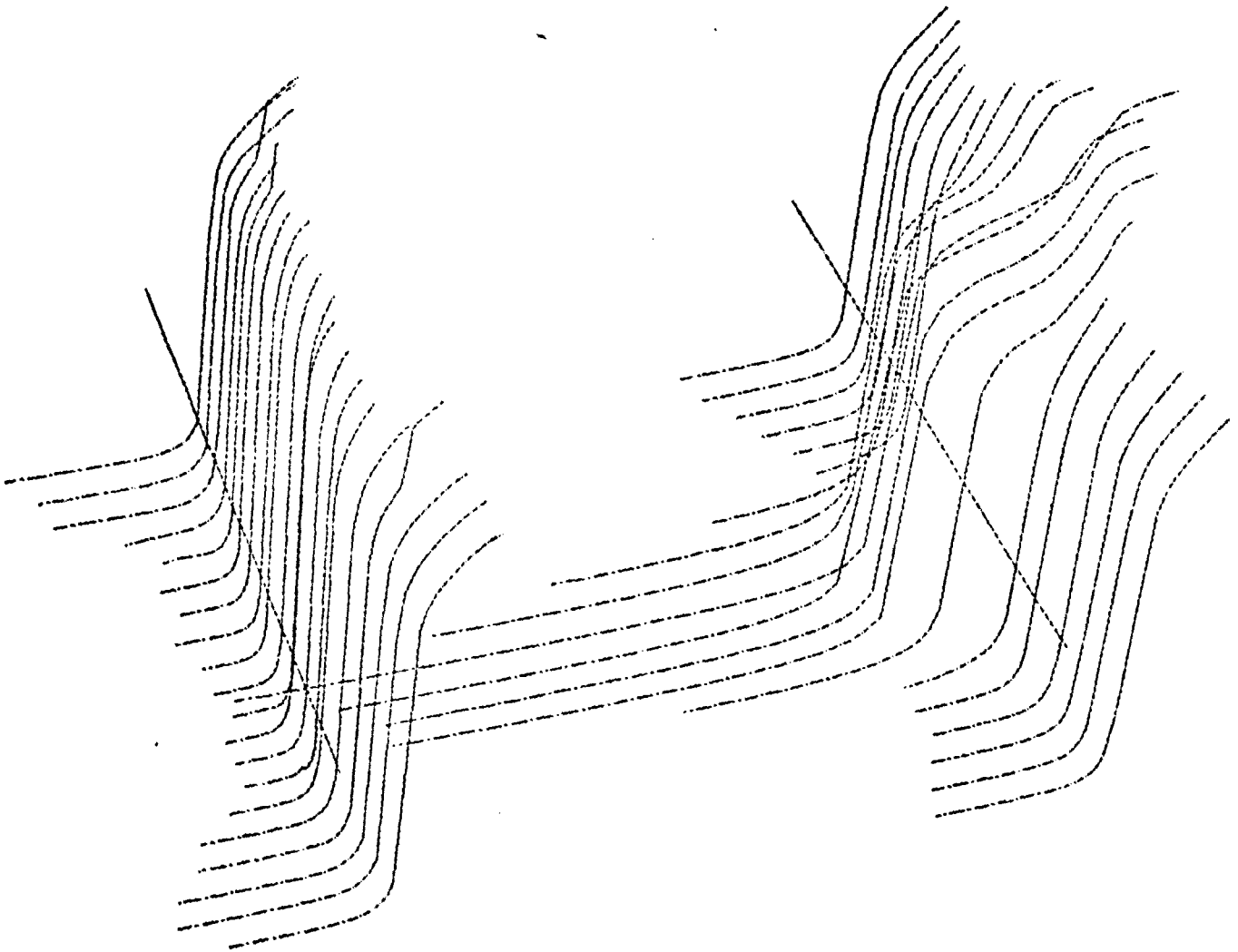


Figure 2

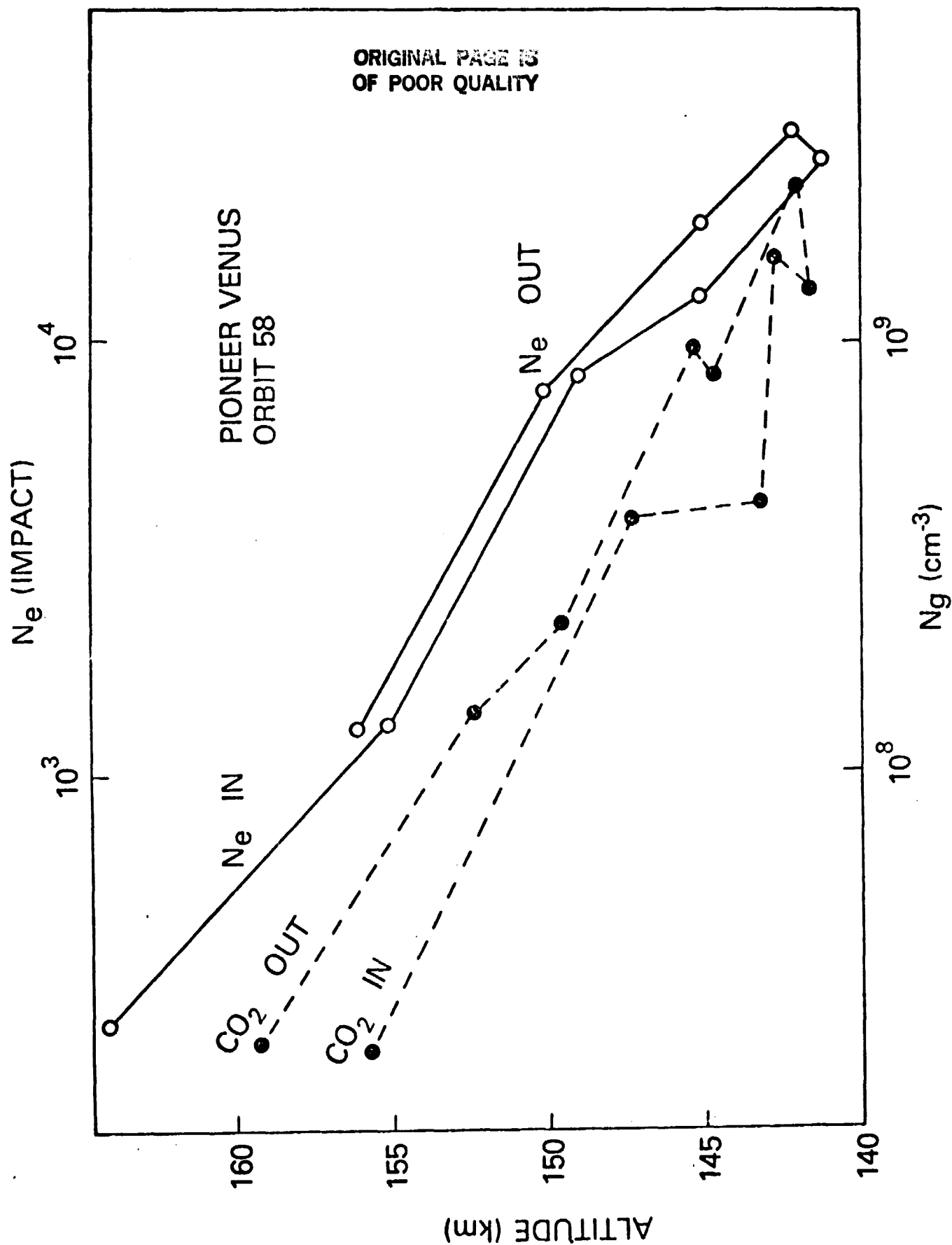
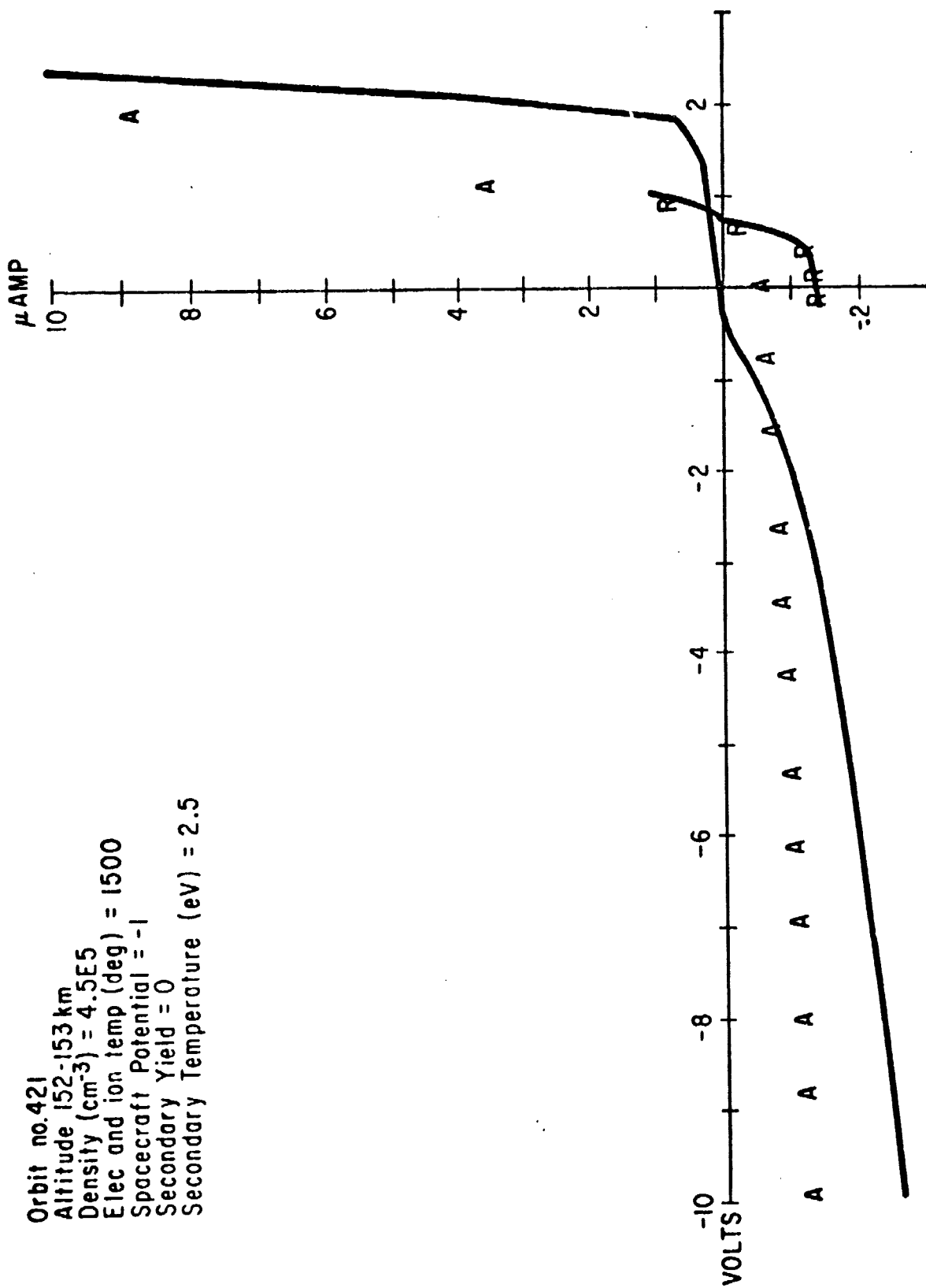


Figure 3

Orbit no. 421
 Altitude 152-153 km
 Density (cm^{-3}) = $4.5\text{E}5$
 Elec and ion temp (deg) = 1500
 Spacecraft Potential = -1
 Secondary Yield = 0
 Secondary Temperature (eV) = 2.5

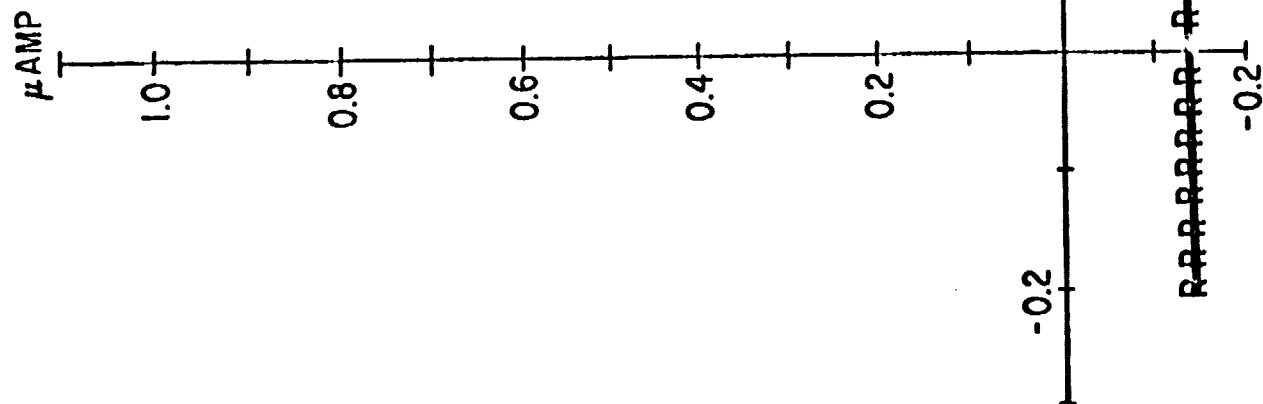
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Figure 4

Orbit no. 421
 Altitude 152-153 km
 Density (cm^{-3}) = $4.5\text{E}5$
 Elec and ion temp (deg) = 1600
 Spacecraft Potential = -1.12
 Secondary Yield = $1\text{E}-3$
 Secondary Temperature (eV) = 2.5

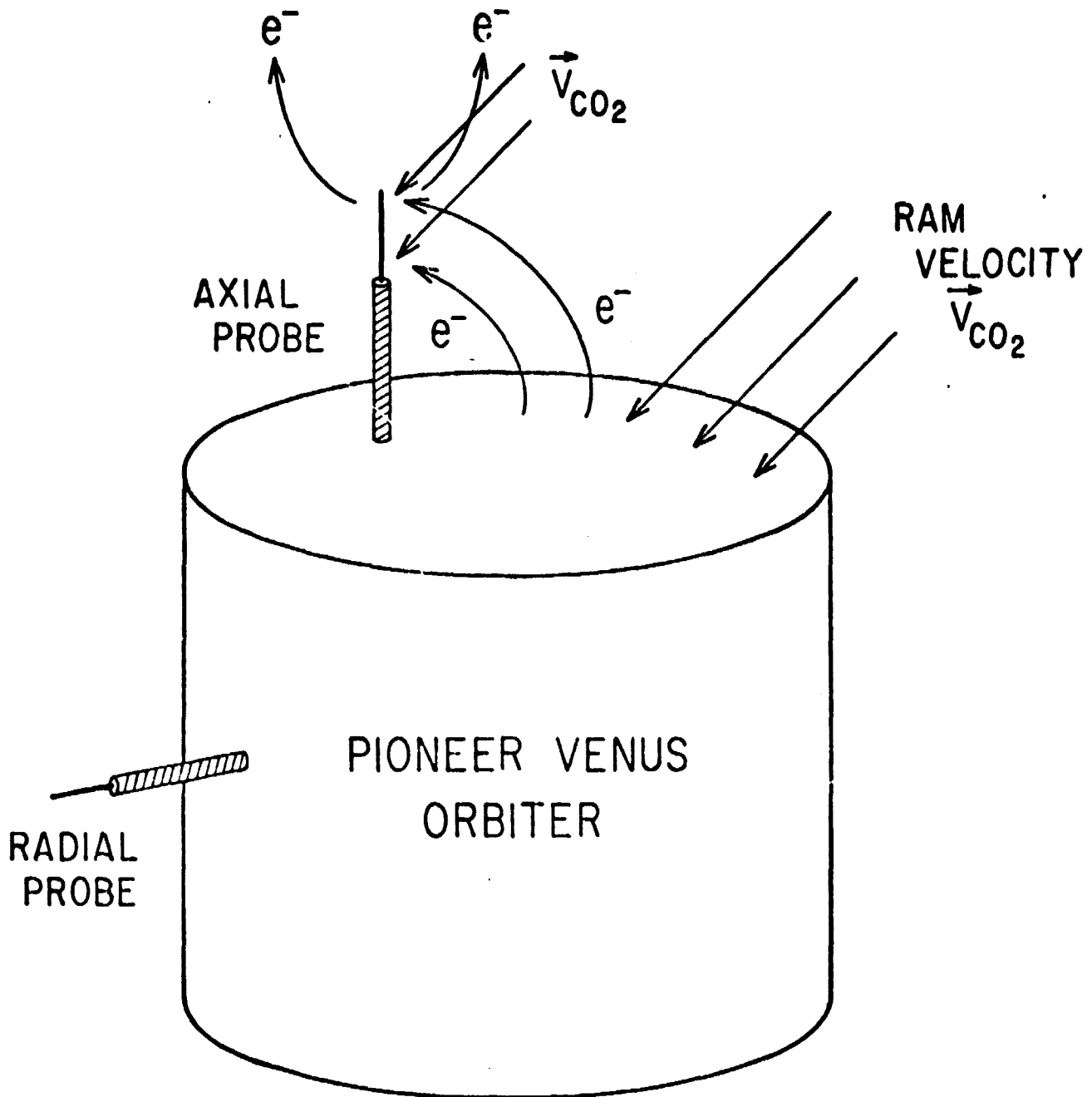


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Figure 5

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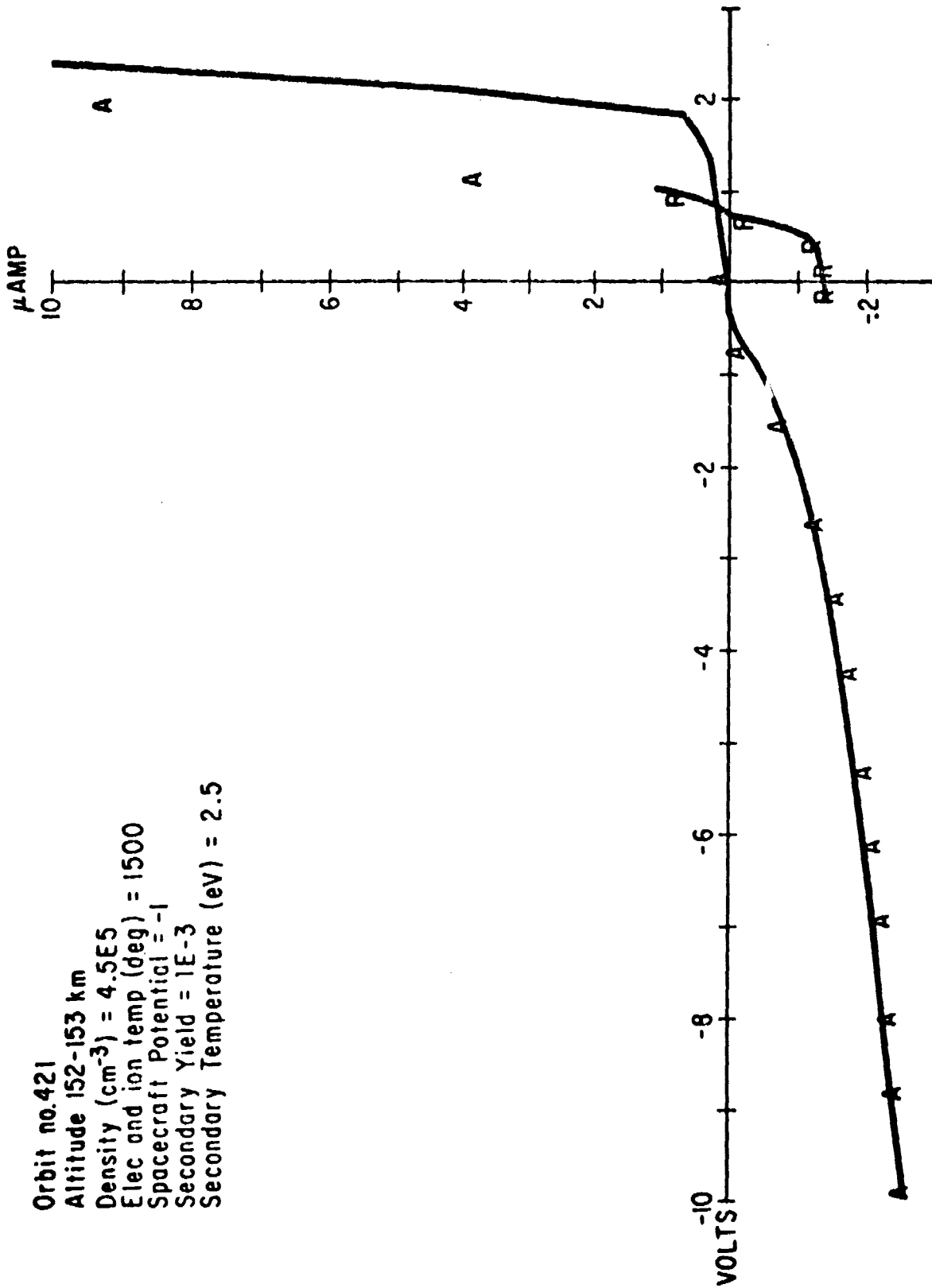


MODEL FOR SECONDARY EMISSION CALCULATION

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Figure 6

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Orbit no. 421
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Density (cm^{-3}) = $4.5\text{E}5$
Elec and ion temp (deg) = 1500
Spacecraft Potential = -1
Secondary Yield = $1\text{E}-3$
Secondary Temperature (eV) = 2.5

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Figure 7

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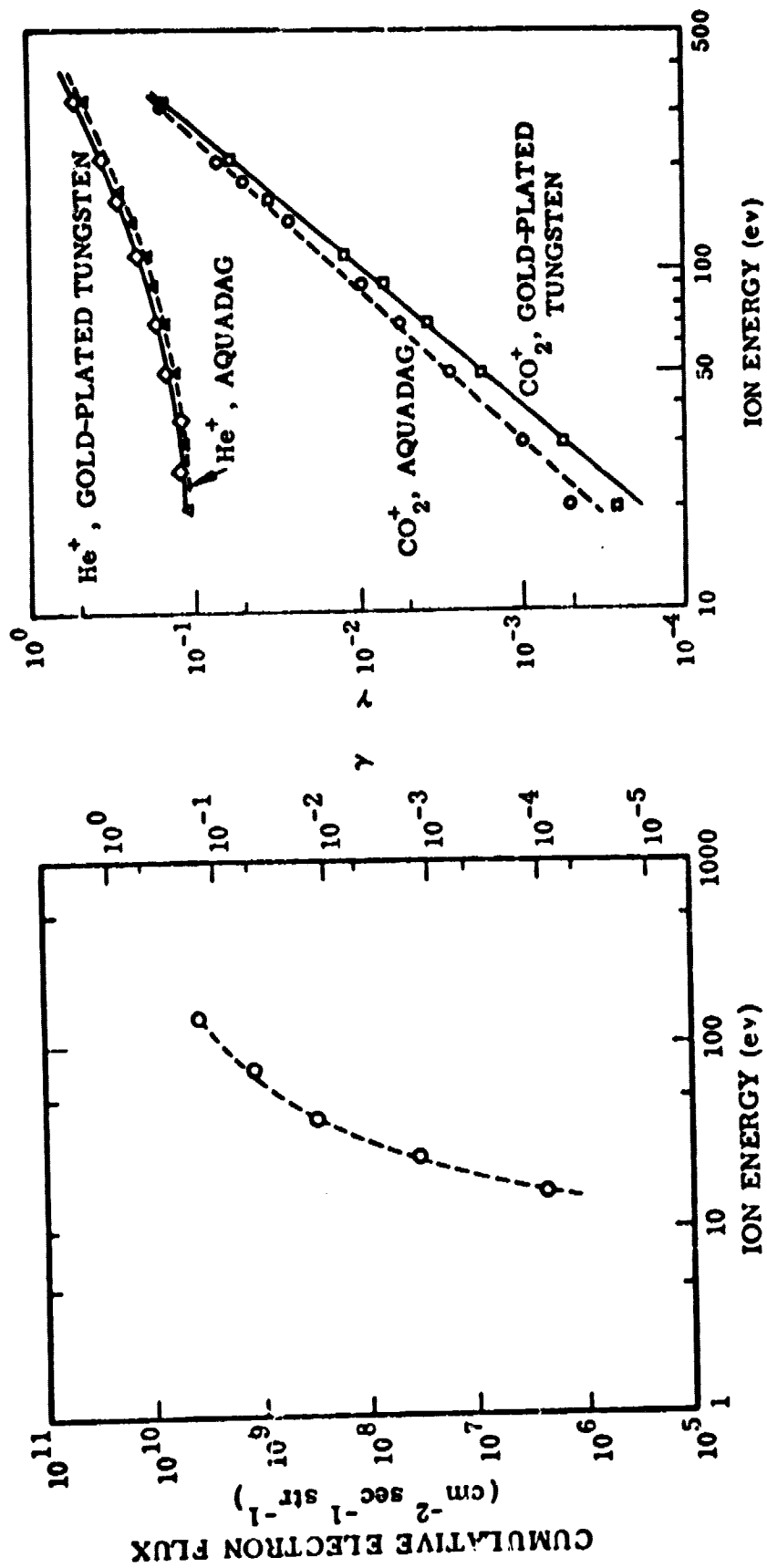
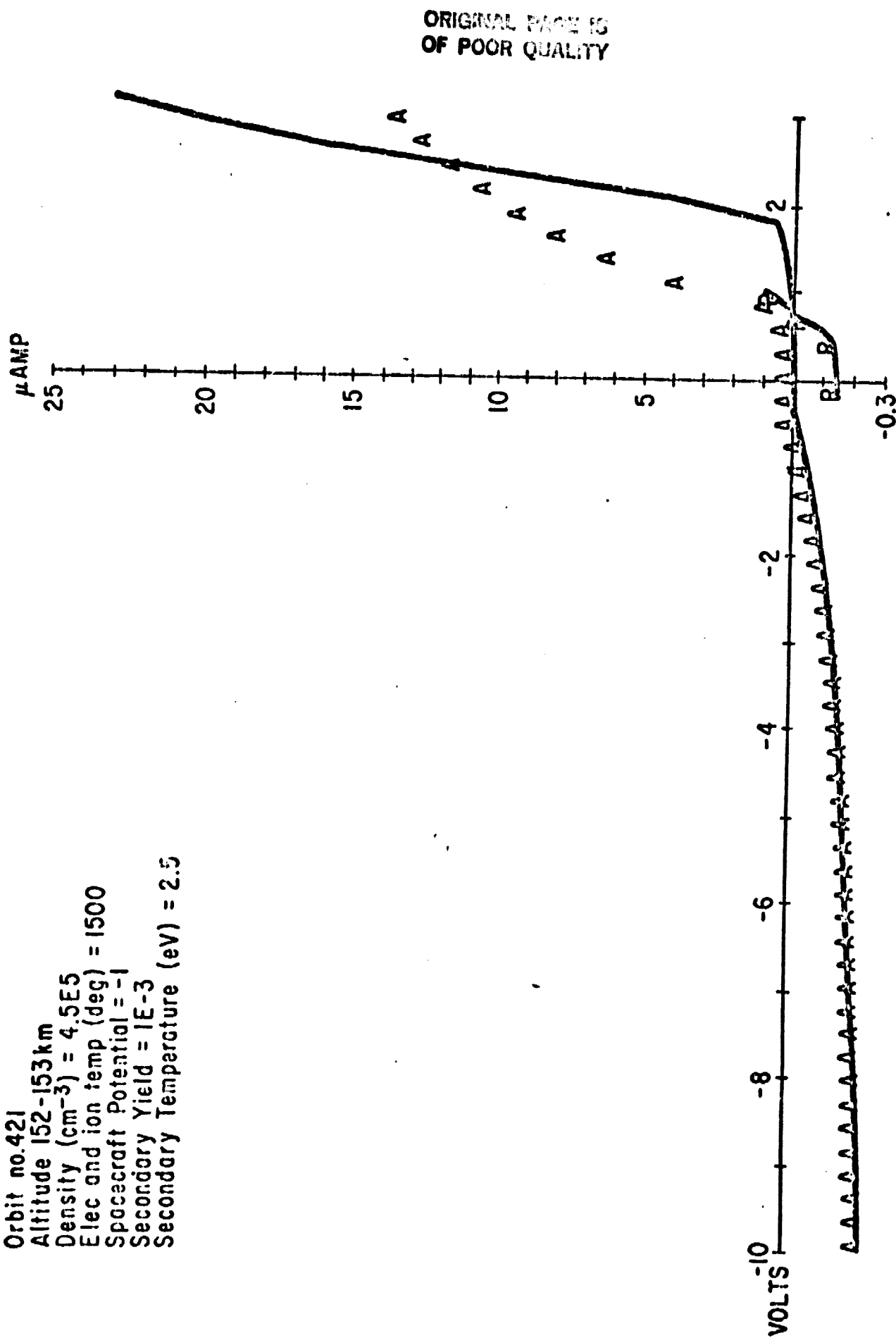


Figure 8

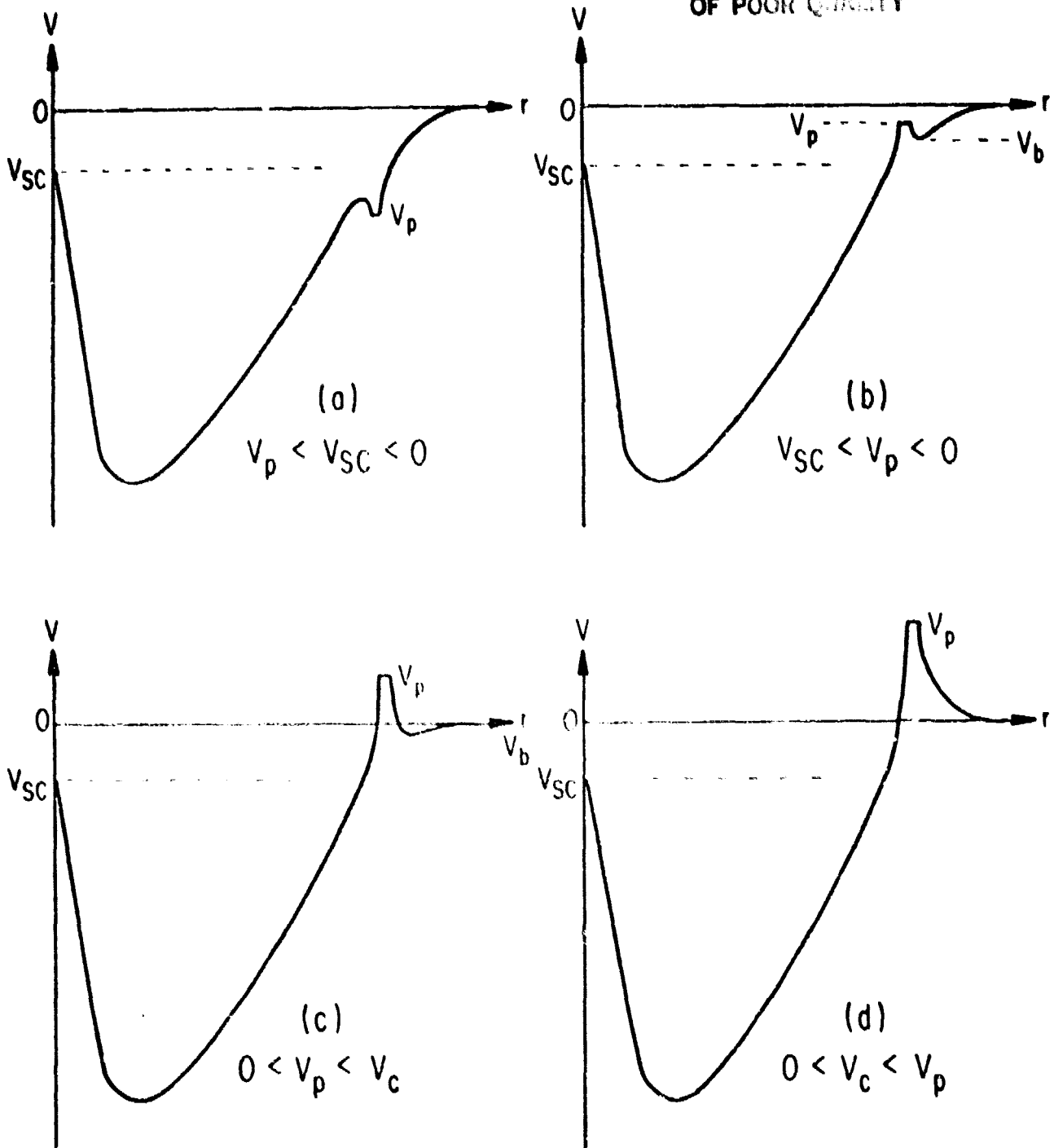
Orbit no.421
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 Secondary Temperature (eV) = 2.5



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Figure 9

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POTENTIAL PROFILES IN SHEATH
SHOWING BARRIER EFFECT

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